COMPARISON OF GREEN HOME ENERGY PERFORMANCE BETWEEN SIMULATION AND OBSERVATION: A CASE OF VIRGINIA, UNITED STATES

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ABSTRACT

The United States has a long-term goal to reduce 50% of energy usage in buildings based on 2010 consumption levels. Home energy efficiency is often measured by laboratory experiments and computational simulation. Thus, there is little to no quantifiable evidence showing the extent of energy efficiency homes can achieve within the larger context of green building standards. The objective of this research is to identify actual home energy performance as an effect of green building technologies by comparing energy use from real-world observations and energy modeling. Results indicate a significant reduction of energy consumption at 43.7% per unit or 43.4% per square foot (i.e., 0.093 m^2) and substantial financial savings at $628.4 per unit or $0.80 per square foot (i.e., $8.6 per m^2) annually. Savings account for 2% of median annual household income or 46% of energy cost expenditures for an American home. Results also identify the construction type as a significant factor, yet building technology is not the only factor influencing a home's energy efficiency. The findings contribute to the body of knowledge in three aspects: (1) simulated energy usage is higher than actual energy usage; (2) energy modeling via simulation tools is particularly accurate for new construction; and (3) energy modeling, especially for existing buildings, is not accurate due to largely varying occupant behaviors.

KEYWORDS

building construction, sustainability, housing, energy efficiency, environmental systems, energy simulation

1. INTRODUCTION

According to the U.S. Department of Energy (DOE 2014), homes and commercial buildings constitute 39% of the nation's energy usage, more than manufacturing or transportation industries. Long-term goals for the U.S. are to reach 50% energy savings in building energy use

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based on 2010 levels of energy usage. To secure these savings, research, development, prescriptive systems and next-generation building technologies are being utilized to advance building systems and energy performance. Based on the U.S. Census Bureau (2016), 23.5% of home improvement projects have completed at least one energy-efficiency project, representing over 9% of all owner-occupied units in the nation, with 32,000 such projects constructed within the last four years.

Energy efficiency is beneficial for homeowners and builder-developers. Homeowners report utility savings and interest in efficiency, despite the upfront costs. Builder-developers also report benefits from energy efficient design, construction operation, and maintenance despite initial costs (Yudelson 2008; Zhao et al. 2017). Since 2006, the architectural, engineering, and construction (AEC) firms have increasingly put employees through certification training and conducted certified projects at increasingly higher levels, showing internal commitment to sustainable principles. While designing and building to a certified standard is now the price of admission for the industry at large, a differentiating point needs to focus on results.

The nation's housing stock is moving towards green building while the understanding of actual performance from such green building technology has not caught up with the trend. In the literature, energy efficiency is often described by laboratory experiments or computational simulation (Clarke et al. 2002; Menassa et al. 2013; Nguyen et al. 2014), which appears to be theoretical. There is little to no observed evidence showing the extent of what energy efficiency homes can achieve within the context of a green building standard. In the absence of such evidence, subjective evaluations of the green building technologies and their contributions to energy use reduction remain likely. Therefore, the objective of this research is to identify home energy performance as an effect of green building technologies through comparing observations and computational energy modeling of energy use. The comparison aims to find discrepancies in home energy efficiency between real-world building use and designated expectations. In reaching this goal, the work is expected to answer the following three questions:

1. Is the actual green home energy performance different from computational simulation?
2. Does the green home energy performance vary by construction type and occupant type?
3. What are the financial savings resulting from green homes and what are their implications for homeowners, builders, and the housing industry?

The next sections of this work are organized as follows. Section 2 will introduce the background of the U.S. residential industry and its green building standards. Section 3 will describe data collection and analysis methods to compare observed home energy efficiency with the estimation from design (energy modeling). Section 4 will describe results of the comparison that indicates the actual home energy performance and variations to the design. Section 5, based on the identified energy performance, will discuss the impacts of green building standards on homeowner expenditures, housing affordability, building codes, and construction costs. Section 6 will outline conclusions drawn from this empirical study.

2. BACKGROUND

2.1 Definition of Home Energy Performance

Green building is gaining acceptance as a sign of excellence in the United States, limiting the options in the market for firms that cannot bring these skills to a building project (McCoy et al. 2012). Energy prices, regulation, and health or safety concerns are all factors that increase the need for the adoption of energy efficient and 'green' practices in the building construction field (Simcock et al. 2014). An inclusive and comprehensive definition of green buildings helps understand and assess building performance.

Many studies have attempted to define high-performance housing; however, there is no one standard definition. Most definitions emphasize energy efficiency, sustainability, and environmentally friendly products (Adomatis 2012). Lewis et al. (2010) defined a green building as one "that is designed, constructed and operated to minimize environmental impacts and maximize resource efficiency, while also balancing cultural and community sensitivity." In the same article, sustainability is defined as development that meets the needs of the present, without compromising the ability of future generations to meet their own needs. Though some may argue that these definitions are more theoretical than practical, within industry these definitions have often been applied while considering the triple bottom lines: balancing environmental, economic, and social goals (Hodges 2005). The Dictionary of Real Estate Appraisal (Appraisal Institute 2010) describes green design and construction as "the practice of developing new structures and renovating existing structures using equipment, materials, and techniques that help achieve long-term balance between extraction and renewal and between environmental inputs and outputs, causing no overall net environmental burden or deficit." The U.S. Energy Independence and Security Act (Sissine 2007) defined a high-performance building as "a building that integrates and optimizes on a lifecycle basis all major high performance attributes, including energy [and water] conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations." Additionally, many professionals are now defining their practices as green without utilizing the prescriptive systems that avow these methods (Tucker et al. 2012). In summary, the authors prefer human-centered energy efficiency to define a building's energy performance, which represents the human–building interactions in a sociotechnical system, including occupant, technology, and building systems.

2.2 Measurement of Home Energy Performance

It is critical to evaluate the designed building's performance after construction in terms of energy consumption, utilities, operations and maintenance, and occupant health (Fowler et al. 2005). While designers and builders might define high-performance buildings as ones that use innovative appliances and technologies, Turner and Vaughan (2012) warns that a high-performance house is not necessarily a "high tech" one (sensors and programmable appliances and equipment are likely to be common features in the near future). The current literature considers consensus-based metrics to evaluate features in a green building project related to specific key indicators (i.e. energy efficiency, indoor air quality, site use, and etc.). Five specific leading determinants directly affect energy consumption in buildings (Bros-Williamson et al. 2016; Emery and Kippenhan 2006; Santin et al. 2009; Yu et al. 2011): building features (e.g., construction type), building technology (e.g., cooling/heating systems), occupant features (e.g., number of occupants), occupant behavior (e.g., activities conducted), and climate (e.g., outdoor air temperature).

In the U.S., three rating systems are Energy Star, the Leadership in Energy and Environmental Design (LEED) for Homes, and the National Association of Homebuilder's (NAHB's) National Green Building Standards (NGBS). A high-performance residential building might be a certified home but every certified home is not necessarily a high performing one. According to Korkmaz et al. (2010), green, sustainable, and high-performance homes are designed and constructed to maximize the energy efficiency of the envelope, mechanical and lighting systems to provide superior quality in the indoor environment for enhancing occupant well-being. In general, homes that can be described as high-performance fall into categories: 1) safer and healthier; 2) more energy and resource efficient; 3) more durable; and 4) more comfortable. Such buildings are being widely adopted for their potential to reduce energy costs and improve the health and productivity of occupants. To achieve the set goals for a high-performance residential project within realistic financial and time constraints, though, superior planning, design, and construction processes are needed. Turner and Vaughan (2012) pointed out high-performance houses as requiring planning, creative and innovative design, and efficient implementation. A high-performance house may also need to fit into federal and state goals, local law or others' needs (the home buyer, architect, builder or manufacturer).

Nationally and regionally, independent building contractors and tradespeople are the stakeholders primarily responsible for implementing green buildings in the residential built environment (McCoy, O'Brien, et al., 2012). These stakeholders are also primarily responsible for either veto or endorsement of innovative products, processes, and systems in residential construction (Koebel 2008; McCoy et al. 2008; Slaughter 1998). According to Ng (2009), "Green building means improving the way that homes and homebuilding sites use energy, water, and materials to reduce impacts on human health and the environment." While the intent and concept is straightforward, early adopters among independent building contractors and tradesmen have recognized a need for communicating specific benchmarks of green building, similar to the "organic" label used for produce. This type of product certification helps to manage expectations, provide measurable deliverables, and establish a metric that can be tied to economic value. Similarly, high-performance construction, such as green building, establishes expectations, measurable deliverables, and metrics for professionals through green building certification programs and training. Both are integral to green building and lend confidence to the risks in implementing a new and relatively unknown system. The industry has moved quickly to address these risks, as almost 50 local and regional green building labeling programs have emerged, many of which have resulted in pieces of national-level programs.

2.3 Environmental and Economic Implications

A variety of influences impact either directly or indirectly household energy use. According to the U.S. Department of Energy (DOE, 2011), the most significant contributors to residential energy consumption include the domains of space heating, space cooling, water heating, lighting, electronics, and appliances. Durak (2011) reviewed previous research, building science fundamentals, energy assessment tools, and commonly accepted business practices in order to identify a comprehensive list of energy consumption influence parameters that drive the demand and expenditure of energy consumption domains in the residential setting. Interrelationships between the energy consumption domains and identified household energy consumption influence parameters were investigated to aid in the future development of more accurate energy models. A summary of the relationship analysis undertaken for the study can be exemplified with the total square footage parameter. Total square footage impacts heating and cooling requirements as well as the lighting energy consumed by a household. The bigger the square footage, the more energy required to meet these needs. Total square footage of a house does not only impact energy consumption items but can additionally affect other influence parameters such as footprint area, the number of rooms, and volume. Changes to the total square footage can, in turn, alter the affected influence parameters and thus impact the energy consumption items they influence.

Home energy efficiency has environmental and economic implications to broader society (Gillingham et al. 2009). Energy efficient housing is critical when considering overall energy demand and consumption, as the impacts are complex and far reaching. The fiscal health of a household can be closely tied to the cost burden of energy expenditures. The energy cost incurred from household operation can be significant; such cost has the potential to create financial hardship for a household. While this is true for all households, irrespective of income level, it holds especially true in the case of low-income households. High-performance homes are not necessarily easy to embrace, either. One of the primary barriers in the green market is the owner's perception of higher initial costs associated with these homes due to added personnel hours and use of innovative materials and technologies (Konchar and Sanvido 1998). Processes and technologies used to deliver green building projects need to remedy this problem (Beheiry et al. 2006; Lapinski et al. 2006). Expenditures resulting from energy consumption largely contribute to a homeowner's costs and becomes a growing consideration during home construction and maintenance. Lee et al. (1995) noted that the cost of energy bills is influenced so strongly by decisions made during design and construction that it necessitates taking a life-cycle perspective when evaluating housing. Lee further stated, "Investment in energy efficiency measures may increase purchase price yet decrease future energy bills." The DOE estimates that the typical household spends approximately 8–14% of their income on energy expenditures. Of this, a third typically is consumed by energy demands for heating and cooling needs (DOE, 2011). This indicates that for the typical American household, heating and cooling costs consume approximately 3–5% of their gross annual income. This percentage is considerable when counting the rising housing cost burden. Today, more than one-in-three American homeowners and one-in-two renters are considered to be cost burdened (Zhao et al. 2015). It is estimated that 12 million renters and homeowners dedicate more than half of their annual incomes to housing expenses. Utility expenses may further affect a homeowner's financial ability to afford to live in a home.

In summary, high-performance homes have significant impacts on the nation's environment and economy, yet a well-established definition and measurement of a high-performance home has not been achieved from the literature. Thus, there is a critical need to explore the residential buildings' realistic energy performance using empirical data analysis. This research fills such a gap by analyzing home energy performance using real-world energy usage and building conditions.

3. METHODS

The presented research was designed to examine home energy performance by comparing observed (actual) and estimated (modeled) energy use. The comparison aims to identify actual home energy efficiency as a result of adopting green building standards and technology. The observed energy consumption data were retrieved from utility bills across a whole year. The estimated energy consumption data were computed using building energy analysis software (REM/Rate software) across individual residential units. The researchers employed comparative statistical analysis and regression analysis to examine differences and to explore contributing factors.

3.1 Data

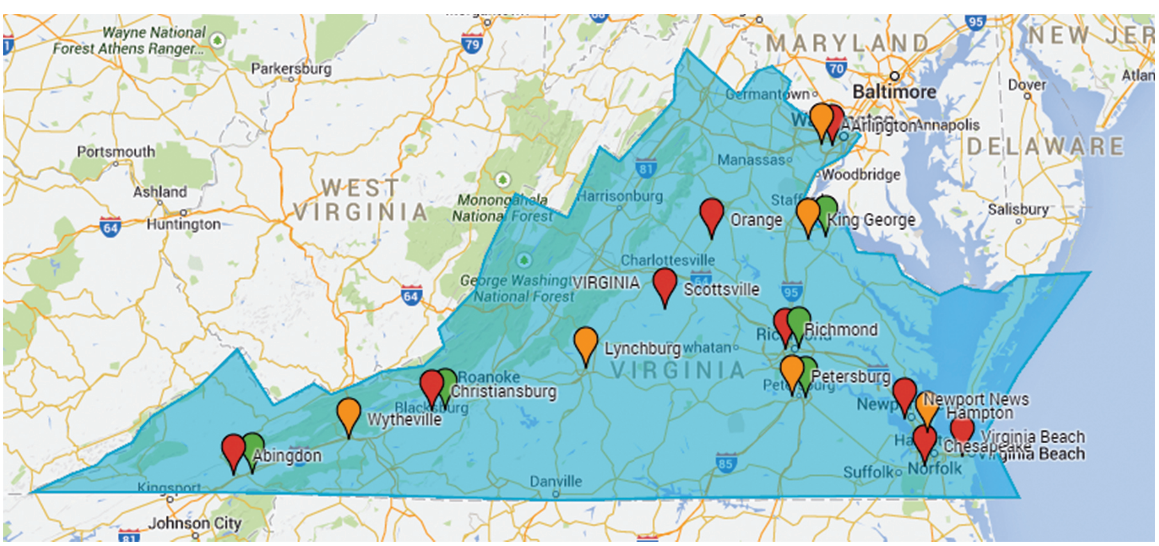
The initial sample in this study contains 312 individual residential units from 16 residential developments across the geography of the State of Virginia (see Figure 1). Based on the Virginia

Housing Development Authority's green building requirements in its Qualified Allocation Plan (QAP), Virginia has recently become ranked highest among states in the southeast U.S. for producing green affordable buildings. Virginia is also one of the top states in terms of attractiveness to tax credit investors as a result of its healthy economy, steady growth, and strong rental housing market. The combination of all of these factors makes residential buildings in Virginia an ideal and available target for this research.

The sample units included varying combinations of construction type (new and renovated) and occupant type (senior occupants and non-senior occupants). New construction project units were located in the counties or cities of Arlington, Hampton, King George, Lynchburg, Petersburg, and Wytheville. Renovated project units were located in the counties or cities of Abingdon, Arlington, Chesapeake, Christiansburg, Orange, Richmond, Scottsville and Virginia Beach. In the U.S., senior occupants are defined as residents of age 55 and above (HUD, 2013). The shortest rental lease included in the data was 12 months. As context, it is noteworthy that this work is the first effort to capture this amount of information for such a large geography and within one common standard.

The sample selection was based on the building's geographical location, application of Energy-Efficiency (EE) retrofit technologies, and sustainable construction practices. The selected units are all built or renovated after 2009, which ensures the availability of state-of-art energy-efficiency technologies for all the units during construction. Another criterion for selection is that the units were required to meet the green building standard of Home Energy Rating System (HERS). HERS presents the energy rating of a home's energy efficiency. The HERS Index is a nationally recognized scoring system for measuring a home's energy performance. Based on the results of field testing and energy modeling, an energy rated home receives a HERS Index score. A score relates the home to the average new standard home construction (commonly termed code-built) in America. A score of 100 is equal to new standard home construction. Lower scores indicate a home performing better than the standard American home. A zero on the HERS index is given to a home demonstrating a net energy demand of zero (Polly et al. 2011) The HERS Index score can be described as a sort of mile per gallon rating for houses.

FIGURE 1. Geographical display of the residential units for data collection.



It provides prospective buyers and homeowners insight into how the home ranks in terms of energy efficiency.

The data were processed and collected through direct on-site visits. The research team organized meetings on-site where property managers and residents were approached with incentives for releasing information. The team collected the utility release forms and partnered with Wegowise, an on-line utility tracking platform, to monitor units and for research purposes only. As a result, two types of data were collected: the utility bills and the building's technical records. The utility bills were collected across one year from June 2013 to May 2014. Such data denote the actual amount of consumed electricity and the money paid to the utility company. The technical records include information about a home's location, area size, building design, mechanical systems for heating/cooling, mechanical system for water heating, insulation in the building shell, and lighting and appliance features. The technical records were later used in energy modeling to obtain the estimated energy use. Particularly, the following 11 categories of technical records were collected for energy modeling (Parker et al. 2012):

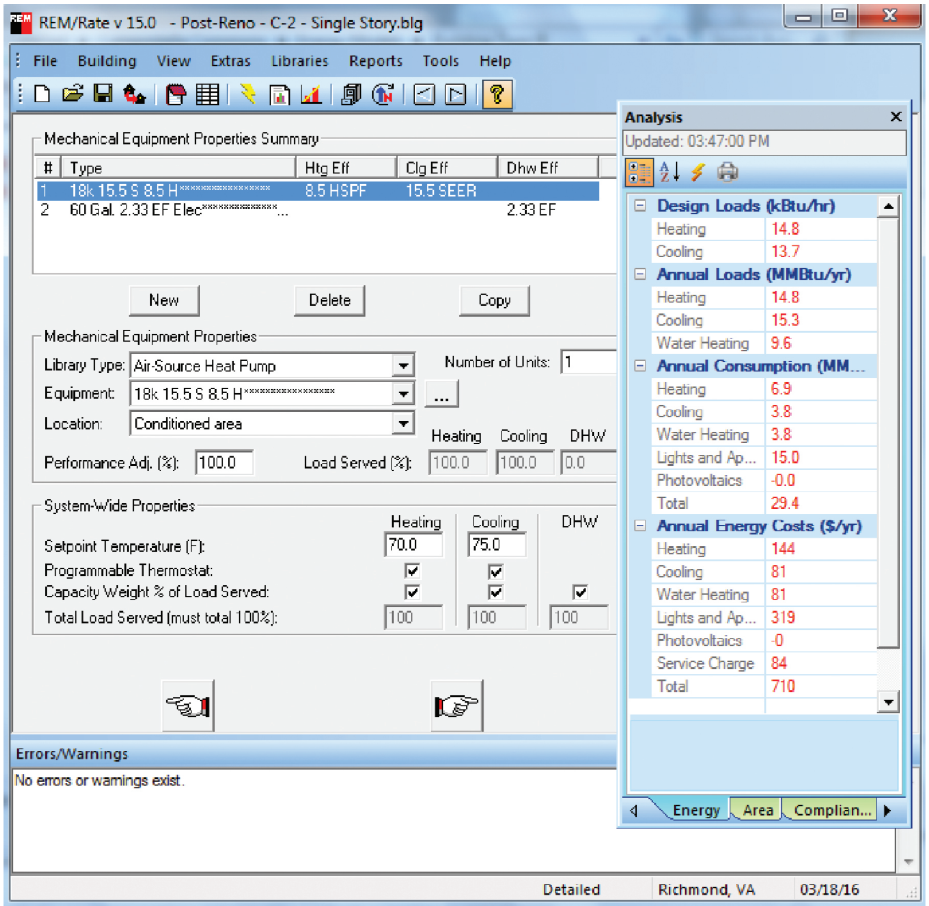
- Conditioned area
- Conditioned volume
- House type
- Air-source heat pump
- Water heating
- Ventilation system
- Programmable thermostat
- R-value
- Windows
- Infiltration rate
- Lighting and appliances

3.2 Analysis

In an effort to accurately assess the residential energy performance, the researchers employed statistical analysis to compare the sample's observed annual energy consumption, estimated annual energy consumption, and the location-based average energy consumption. Data of the observed energy consumption are from the collected utility bills. Data of the estimated energy consumption are from the energy modeling of collected technical records. The average energy consumption information is retrieved from public data sources. Finally, data from a total 202 qualified samples were used in the statistical analysis due to missing values.

In obtaining the estimated energy use, the researchers input the technical records into industry-standard energy models of the intended design and construction on energy performance for each occupant household unit. Model estimates of utility costs are per unit for designs and provide a nominally estimated design effect. Residential energy modeling and analysis was performed in the REM/Rate software (see Figure 2), which calculates heating, cooling, hot water, lighting, and appliance energy loads, and consumption and costs for new and existing single and multi-family homes. Climate data which are available for cities and towns throughout North America are also incorporated into the energy modeling. The software has been widely adopted in the building research and energy auditing practice (Mosteiro-Romero et al. 2014; Sawhney et al. 2002; Walsh et al. 2003), and thus is believed to be an efficient home energy analysis tool.

FIGURE 2. Interface of REM/Rate software used for energy modeling.



Analytical techniques include *t*-test, correlation analysis, and linear regression. Particularly, a linear regression technique is used to identify the correlation between energy consumption and building technology. The regression equation is described in Eq. 1, as follows:

$$C = \beta * T + \varepsilon \tag{1}$$

where C is the per-unit energy consumption, T is the green building technology level, which is represented by the HERS index, β is the coefficient, and ε is the error term. In an effort to accurately assess the residential energy consumption and efficiency, the researchers collected two sources of energy data and analyzed them, as previously discussed. Each HERS certification acts as an official verification of energy performance by the U.S. Department of Energy and the U.S. Environmental Protection Agency. The HERS certification provides a HERS index which ranges from 0 for a net-zero building and 100 for a conventional reference building (Mosteiro-Romero et al. 2014).

The researchers assess the economic influences by computing the financial savings. The following benefit equation (Eq. 2) converts the annual energy savings into monetary values, and the rate equation (Eq. 3) leads to the saving rate that indicates the ability of energy saving:

$$S = E_o - E_a = \sum_{i=1}^{n} \left(C_{oi} - C_a\right) P_i \quad (2)$$

$$R = \frac{E_o - E_a}{E_a} = \frac{\sum_{i=1}^{n} \left(C_{oi} - C_a\right) P_i}{\sum_{i=1}^{n} C_a \cdot P_i} \quad (3)$$

where, S is the yearly financial savings (in U.S. dollar), R is the ratio of energy saving, E_o is the observed yearly energy expenditures, E_a is the average energy expenditures, C_{oi} is the observed yearly energy use for the ith residential unit, the C_a is the location-based average home energy usage, and P_i is the ith unit based utility price. The price was converted into a 2014 dollar value to mitigate the influence from inflation of buying power.

4. RESULTS

4.1 Overall Home Energy Consumption

Table 1 summarizes annual energy consumption of units with complete records in the sample (n = 202 residential units). The estimated energy consumption is simulated based on each unit's specific building systems. The authors expected units to be energy efficient after adopting green building standards. Results from energy simulation show an overall energy consumption of 8,000.1 kWh per unit per year, lower than the statewide average of 12,204 kWh. Moreover, the estimated energy consumption for divisions by construction type and occupant type are less than the state average: new units 7,439.6 kWh, renovated units 8,424.1 kWh, units for senior residents 7,245.4 kWh, and the units for non-senior residents 8,409.1 kWh. Results from variance analysis indicate that new developments and non-senior units contain higher variability in energy usage.

Interestingly, observed energy consumption is also lower than estimated. Results from statistical analysis (Table 1) show that the observed energy consumption is 6,819.7 kWh per unit per year, indicating 1,180.4 kWh lower than the estimation. Such paired difference is statistically significant at a 99% confidence level ($t = -5.07$, $p < 0.001$). Moreover, data analysis also indicates significant reductions of energy consumption at a 99% level in the following building divisions: renovated units (2,065.0 kWh, $t = -7.44$, $p < 0.001$), units for senior residents (769.9 kWh, t = 02.73, $p = 0.008$), and units for non-seniors (1,403.5 kWh, $t = -4.33$, $p < 0.001$).

While Table 1 lists the paired differences of estimated and observed energy consumption, Figure 3 plots these data. In the plot, a coordinate with positive value (above 0) on the y-axis denotes a unit with higher observed energy consumption, while a coordinate with negative value (below 0) denotes a unit with lower observed energy consumption. Results show that the mean difference is negative, which confirms reduced energy consumption in a real-world setting of observed usage. Figure 3 also illustrates the variability of energy performance across units. While the maximum variance is substantial, either positive or negative, for both new and renovated units, these outliers seem unlikely to be associated with building conditions, design, and construction. Rather, the authors posit that the variance is a result of differing residential behaviors (Ouyang and Hokao 2009; Zhao et al. 2016).

TABLE 1. Summary of annual energy consumption.

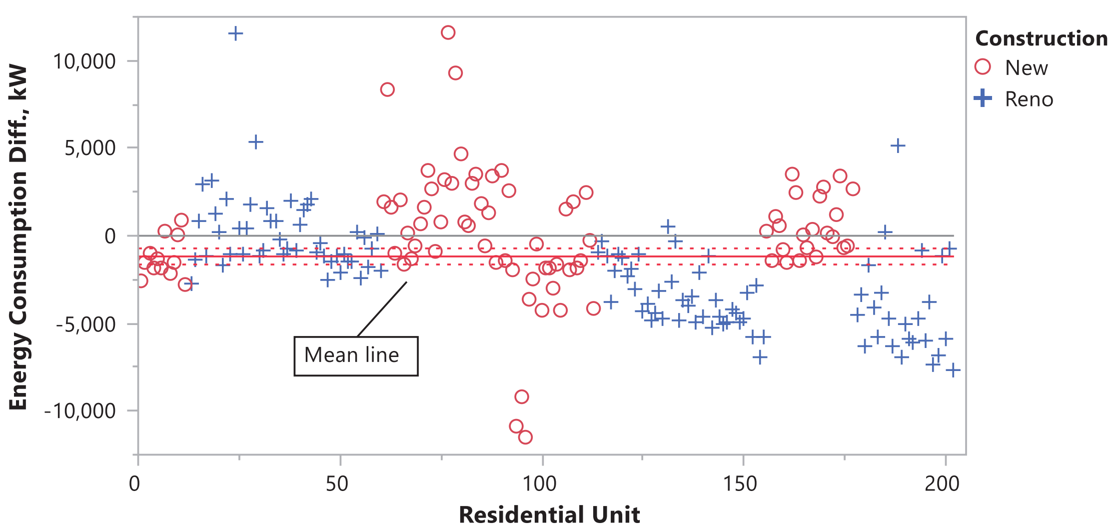
Division	Est. (kWh)	Obs. (kWh)	Diff. (kWh)	N	Std Err	t	p	Upper 95%	Lower 95%
Overall	8,000.1	6,819.7	−1,180.4	202	233.0	−5.07**	<0.001	−720.9	−1,639.9
New	7,439.6	7,428.4	−11.2	87	362.9	−0.03	0.9755	710.2	−732.6
Renovated	8,424.1	6,359.1	−2,065.0	115	277.7	−7.44**	<0.001	−1,514.9	−2,615.0
Senior	7,245.4	6,476.6	−769.9	71	281.7	−2.73**	0.008	−207.1	−1,331.6
Non-Senior	8,409.1	7,005.6	−1,403.5	131	324.4	−4.33**	<0.001	−761.7	−2,045.3

Note: Est = Estimated; Obs = Observed; Diff = Difference; Round-off errors may apply; ** = Significant at 99%.

4.2 Level of Green Building Technology

Figure 4 offers a visual representation of linear regression results for annual energy consumption (as the dependent variable) dependent on building technology (as the independent variable). In the analysis, building technology is represented by the unit's individual HERS Index score, an industry standard asset rating used to evaluate a home's performance compared to an equivalent home built to the 2004 International Energy Conservation Code (IECC). As an example, a HERS score of lower than 90 means that a home is 10% more energy efficient than standard new construction (current code-based construction). In our research, most HERS scores from the analyzed residential units range from 50 to 90, while three are less than 20 owing to net-zero energy building technology. The mean HERS score is 68.2. The HERS scores suggest that these units have incorporated appropriate building technology to improve energy performance, which

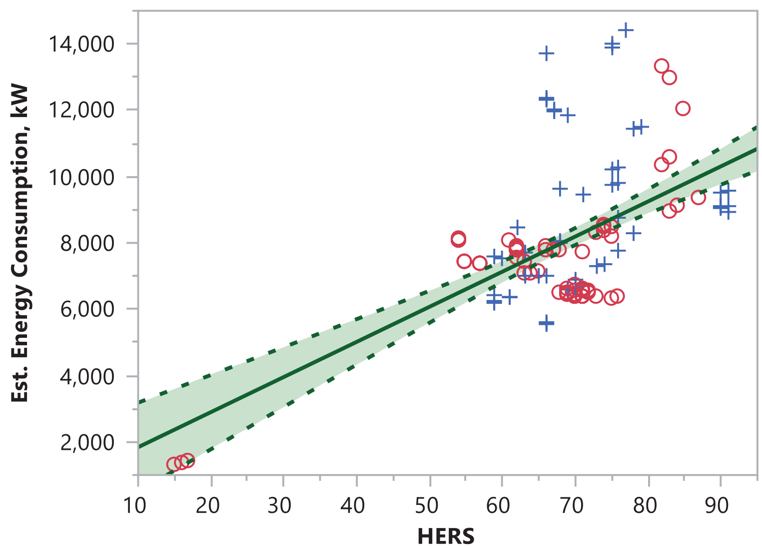
FIGURE 3. Plot of differences between the estimated and observed annual energy consumption.



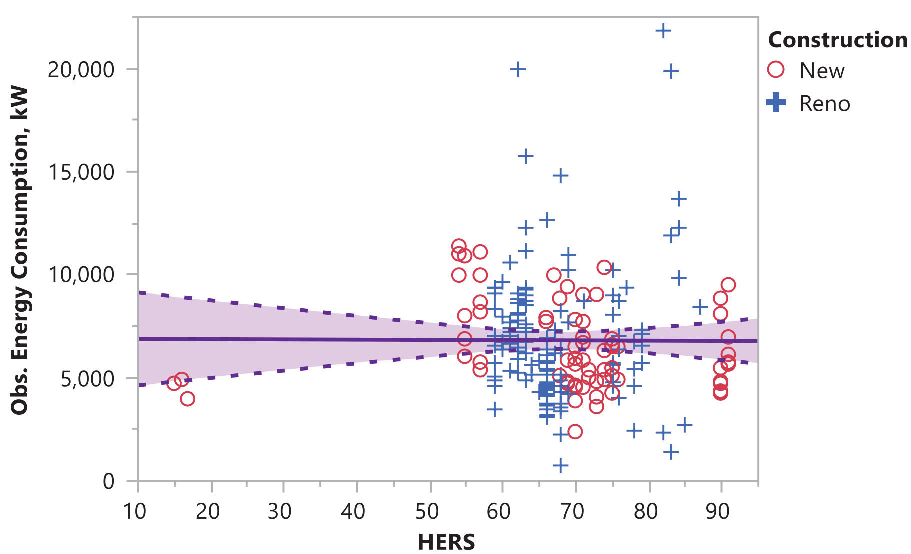
was expected to be 31.8% (based on the average HERS score of 68.2) more energy efficient over standard new construction.

We also hypothesize that a lower HERS score (i.e., higher building technology) leads to lower energy consumption (i.e., higher energy efficiency). Coupling results from Figure 4 and Table 2, estimated energy usage positively correlates with HERS scores ($\beta = 105.9$, $R^2 = 0.30$). In other words, the lower the HERS score, the lower the estimated energy usage level and the higher the score the more energy efficiency is reduced (a negative correlation). The correlation is statistically significant at a 99% confidence level ($F = 84.7$, $p < 0.001$), confirming our

FIGURE 4. Linear regressions of annual energy consumption over building technology in (a) estimated; and (b) observed.



(a)



(b)

TABLE 2. Parameters in the linear regressions.

	Coefficient (β)	Disturbance (ε)	*F*	*p*	R Squared	Mean Square Err
Estimated	105.9	780.6	84.7**	<0.001	0.298	1786.7
Observed	−1.2	6901.6	<0.1	0.950	<0.001	2997.7

Note: Round-off errors may apply; ** = Significant at 99%.

association between building technology and simulated energy performance. The R-squared value shows that only 30% of energy variance can be explained by building technology (i.e., HERS) and indicates additional predictors other than building technology. As a result of this strong correlation, we are able to posit the following formula that allows us to estimate annual energy consumption in kWh based on a 2010 HERS score:

$$\text{Estimated Energy Consumption (kWh/year)} = 105.9 * \text{HERS} + 780.6$$

In contrast, results from observed energy consumption exhibit a non-linear correlation between building technology and observed energy performance. In other words, some units had excellent building systems according to HERS; however, they did not demonstrate accordingly remarkable energy efficiency. For example, in some units, the annual energy usage was estimated at less than 1,500 kWh per unit but observed at approximately 4,600 kWh per unit. Consequently, findings suggest that building technology might not be the only dominant factor for a home's energy efficiency and more variable than the HERS score itself.

4.3 Construction Type

Table 3 lists comparative values for energy consumption of new and renovated developments. Analysis indicates that the new residential homes are estimated to have lower energy usage (7,439.6 kWh) than renovated homes (8,424.1 kWh). Such a difference between new and renovated units is significant at a 99% level ($t = 3.464$, $p < 0.001$). On the contrary, observed results indicate new units use more energy (7,428.4 kWh) than renovated units (6,359.1 kWh). The difference in observation is statistically significant at a 95% level ($t = -2.466$, $p = 0.015$).

TABLE 3. Comparison of annual energy consumption by construction type.

	Construction Type	Mean (kWh)	Std Err	Upper 95%	Lower 95%	Diff. (kWh)	*t*	*p*
Estimated	New	7,439.6	187.4	7,812.1	7,067.1	−984.5	3.464**	<0.001
	Renovated	8,424.1	213.6	8,847.3	8,000.9			
Observed	New	7,428.4	358.9	8,141.8	6,715.0	1,069.3	−2.466*	0.015
	Renovated	6,359.1	243.5	6,841.4	5,876.8			

Note: * = Significant at 95%; ** = Significant at 99%.

The finding confirms the important role of construction type on energy efficiency. The finding also suggests that while new units are expected to be higher in energy efficiency (a clean slate for designing and constructing the unit); in fact, renovated units can achieve better energy performance. It is also important to note that new units in our sample included a larger number of families with more than one person.

4.4 Occupant Type

Table 4 lists comparative values for energy consumption between senior and non-senior occupants. Analysis indicates that in both estimated and observed usage, units designed for senior residents consume less energy than those for non-senior residents. Estimated energy usage for seniors is 1,163.7 kWh less per year while observed usage is 529.0 kWh less per year. According to building simulation models, senior units should have significantly lower energy consumption ($t = 4.238$, $p < 0.001$). However, observed usage does not support the simulation indicating less significance in the difference ($t = 1.375$, $p = 0.173$) between senior and non-senior occupants. Results suggest that the design of the occupant type currently impacts a unit's energy consumption less than expected.

4.5 Energy and Financial Savings

Table 5 summarizes the annual energy and financial savings as a result of the incorporation of building energy efficient technologies. Results indicate that per-unit energy savings are 5,384.3 kWh per year, which is 28.1% greater than estimated. Combining the average utility rate of $116.7 per 1000 kWh (U.S. Energy Information Administration 2014) for Virginia, such savings equal $628.4 per year. Findings suggest that the per-unit savings are estimated to be 34.1%, yet are observed at an even larger amount of 43.7%.

The researchers also calculated the savings by conditioned area (in square footage), considering that the per-unit data might not necessarily provide a complete picture of energy usage. Analysis indicates that the actual energy savings are 6.8 kWh per square foot (equals to 73.2 kWh/m^2), which equals to $0.80/sf (equals to $8.6 per m^2). These resulting savings were then compared with national energy usage data (U.S. Department of Energy 2011). Results of saving rates from Table 5 show that area-based savings are as much as 43.4% of new standard construction for multifamily homes.

Overall, findings from per unit and per area savings are highly consistent, both of which demonstrate that the units are more than 40% energy efficient than standard new construction built to IECC requirements.

TABLE 4. Comparison of annual energy consumption by occupant type.

	Occupant Type	Mean (kWh)	Std Err	Upper 95%	Lower 95%	Diff. (kWh)	*t*	*p*
Estimated	Senior	7,245.4	190.4	7,625.1	6,865.7	1,163.7	4.238**	<0.001
	Non-Senior	8,409.1	197.8	8,800.5	8,017.7			
Observed	Senior	6,475.6	252.1	6,979.5	5,973.7	529.0	1.367	0.173
	Non-Senior	7,005.6	293.6	7,586.5	6,424.7			

Note: ** = Significant at 99%.

TABLE 5. Summary of annual energy and financial savings.

	Savings per Unit			Savings per Sq. ft.		
	Energy (kWh)	Savings ($)	Rate (%)	Energy (kWh)	Savings ($)	Rate (%)
Estimated	4,203.9	$490.6	34.1	5.3	$0.60	34.1
Observed	5,384.3	$628.4	43.7	6.8	$0.80	43.4

5. DISCUSSION

5.1 Homeowners and Energy Expenditures

According to Adomatis (2010), the concept of ensuring performance in housing contains roots in the business concepts of quality and customer satisfaction. Performance is integral to the assurance of quality in housing, which might, in turn, lead to satisfaction. Quality is subjective, though, and may be understood differently by consumers within and across markets. Summary measures of performance can help reduce speculation of quality for a product/service, a major barrier to the adoption and diffusion of green technology.

Increasing home operating cost is a major factor in assessing building performance. Residents finding themselves on the threshold of affordability can see their energy costs push housing expenditures beyond the normally accepted 30%. The globally trending rise in energy consumption and cost will further the financial burden placed on residents if energy costs escalate at the projected exponential rate (DOE, 2011). Additional hardships are realized because month-to-month and year-to-year energy costs are not constant. As household energy demands fluctuate, dependent on year-to-year weather conditions, so do monthly energy costs. This erratic monthly variance in the percentage of income allotted for housing is destabilizing to family finances.

Results from this study suggest that the actual energy savings are 6.8 kWh per square foot (equals to 73.2 kWh/m^2), which equals to $0.80/sf (equals to $8.6 per m^2). Compared with national energy usage data (DOE, 2011) results show that area-based savings are as much as 43.4% of new standard construction for multifamily homes. Further, findings from per unit and per area savings are highly consistent, demonstrating more than 40% energy efficiency than standard new construction built to 2004 IECC requirements.

The impact is especially important to the low-income household. A low-income household is one that earns less than half of the median income for their area. For these households, the cost of housing alone can take a significant portion of their gross income within the generally accepted rule that housing cost should ideally not be more than 30% of one's gross income; it is often the case that low-income households spend more than 30% of their gross income on housing and associated operating cost.

All households are affected by energy expenditures and the rising cost of energy. However, not all households have the financial means to simply pay more for their required energy expenditures. Therefore, those households with low incomes will be burdened the most by future inflation. In examining the role energy expenditures play in housing affordability, Lee et al. (1995) calculated that energy cost burden accounted for 13% of housing expenditures for households above the low-income level. Comparatively, for a low-income household 25% of their total housing expenditures were dedicated to energy. Of the total energy consumed, over 40% was consumed by space heating and air conditioning.

5.2 Housing Policy and Affordability

Findings of energy performance comparison within the concept of green building standards provide quantifiable evidence for policy makers in the realm of housing and development. Whether it is a rental payment or a mortgage payment, housing costs make up a large percentage of Americans' monthly expenditures. The U.S. Department of Housing and Urban Development (HUD) uses residents' ability to afford monthly expenditures, such as housing, to determine policies for housing assistance and affordable housing creation. The provision of affordable housing is vital for promoting vibrant communities and strong economies. The relationship between energy costs and housing affordability has been long established in the research (Lee et al. 1995) and in public policy (e.g. LIHEAP, weatherization, housing subsidy utility allowances, DOE-HUD initiative on energy efficiency in housing). A basic internet search for "affordable housing" and "energy efficiency" produces 1,450 matches in the Energy Citations Database and 788 matches in peer-reviewed publications. Although the impacts of the weatherization program have been extensively documented, the benefits of energy efficiency in new and renovated affordable housing are typically assumed and have not been rigorously analyzed.

Throughout history, the U.S. has used different approaches to alleviate housing payment burdens for low-income households. Federal government programs include public housing, housing choice vouchers, community development block grants (CDBG), and most recently, the Low-Income Housing Tax Credit (LIHTC). Today, the LIHTC is the largest low-income rental subsidy in the U.S and is an item of the Internal Revenue Code, not a federal housing subsidy (Schwartz 2011). To understand the impact housing policies can have on affordable housing, it is essential to understand the role of housing policy within the LIHTC. Since the income of renters in the LIHTC program is significantly below the Area Median Income (AMI), financial savings could heavily affect their annual income. For a typical America household, the residential energy cost expenditure (e.g., for heating and cooling) approximately accounts for 3–5% of their gross annual income. Combining average expenditures with these savings, units in the Virginia LIHTC are significantly lessening household energy burden (40–46% in some cases) due to energy efficient units.

Further, while housing expenditures applied toward a mortgage (including additional construction cost for higher quality) build equity, energy expenditures add nothing to a family's accrued value of ownership in a property. It is easy to become energy insecure when a household experiences at least one of the following in a year (Elevate Energy 2014): they are threatened by utility shutoff; one of their utilities is shut off or they are refused delivery of a heating fuel; they go with a day of no heat or cooling because of the inability to pay bills; or they are forced to use a cooking appliance as a source of heat.

5.3 Residential Building Industry

The impact that energy efficient building design, construction and 3rd party verification has on housing costs plays a key role in determining the future of EE policies in green building standards. By studying 3rd party verified rating systems and their integration of energy efficient building practices, there is now a greater understanding of predicted vs. measured energy efficiency in high-performance residential buildings. Results from this study suggest observed energy savings is 5,384.3 kWh per year (28.1% greater than estimated) with savings equal

$628.4 per year on average. While per unit savings are estimated to be 34.1%, they are observed at an even larger amount of 43.7%.

In general, housing is constructed as inexpensively as permissible for its market type by meeting the minimum requirements for current code standards. This is done in order to keep first costs low, thus ensuring clients' financial accessibility and maximum profitability for developers and homebuyers alike. In the past, little consideration was given towards energy efficiency and the additional expense of operation (primarily conditioning cost) that result from building to minimum standards. Such practices have been found to be common when attempting to create housing accessible to low-income households. As a result, housing built to a target cost point with short-term financial motives and to minimum standards is often not as energy-efficient as it could be. This lack of energy efficiency creates a higher operating cost when compared to high-performance construction methods and materials.

For example, a green building certification under EarthCraft Virginia requires that a development meet basic criteria: 1) meeting energy modeling performance goals, 2) meeting minimum worksheet requirements and points thresholds (variable depending on new/renovation or single family/multifamily, 3) pass all required inspections/site visits including air sealing, pre-drywall, and final testing (including enclosure and duct leakage testing). According to EarthCraft, the additional construction costs for a certified home are no more than 3% higher than that of traditional construction. EarthCraft Virginia maintains that homes built to their specs are in actuality cheaper when factoring in long-term energy savings. A recent report by the Southface Energy Institute (Roberts et al. 2016) suggests that the green developments are performing better than the non-green developments in terms of construction and development costs, energy efficiency and utility costs and satisfaction.

5.4 Building Energy Code Adoption

Results from this study suggest that not only does the actual average energy use per unit vary considerably, the estimated energy use of design and construction modeling varies in the sample as well. Estimated model average variability suggests that design and construction for energy efficient units could be performed within tighter values across the sample, which could result in increased unit efficiency on average. Green building rating systems utilize the most current IECC provisions developed by the International Code Council as a minimum performance benchmark. In the U.S., state or local jurisdictions decide the year of building code adoption (Zhao et al. 2015), which leads to the variability of building codes. In other words, some states or cities adopt newer codes while others use older codes. For example, the HERS reference home is based on IECC version 2004, using the language "standard new home, which meets the current industry standard for home energy efficiency. Virginia has adopted the 2012 IECC as of this study while the developments included are closer to 2009 IECC requirements. Since residential energy codes have increasingly become prescriptive over the last 10 years, findings from this study suggest that there could be an opportunity to utilize performance driven methodologies to more affordably meet the goals of future energy codes.

6. CONCLUSION

This study investigates energy consumption and savings for energy efficient housing units as a result of adopting green building standards in the U.S. Towards this goal, researchers analyzed data on 202 residential units in the State of Virginia with complete records of simulated energy usage, observed energy usage, and incorporated energy efficiency technologies across one year through utility records. The sample units included varying combinations of construction type (new and renovated) and occupant type (senior residents and non-senior residents). Results from this work have identified a significant reduction in energy consumption at 43.7% per unit or 43.1% per square foot (i.e., 0.093 m^2), which indicate a high level of energy efficiency achievement. The results have also identified excellent financial savings due to energy efficiency technology at $628.4 per unit or $0.80 per square foot (i.e., $8.6 per m^2) in a year, which accounts for up to 2% of the household annual income or 46% of energy cost expenditures for an American home. Such findings are different from previous work which estimated that using high-performance energy design and construction technologies would save 25–30% of energy use over standard new construction practice. Moreover, findings suggest that construction type is a significant factor to a housing unit's energy efficiency, while the building technology is not the only dominant factor to a house's energy efficiency.

The findings contribute to the body of knowledge in three aspects: (1) simulated energy usage is higher than actual energy usage; (2) energy modeling via simulation tools is accurate for newly constructed buildings only; and (3) energy modeling, especially for existing buildings, is not accurate due to largely varying occupant behaviors. The findings also provide implications for policy makers by suggesting a rigorous quantification of gross and net economic impacts of energy efficient housing and by distinguishing energy usage differences through estimated, actual, energy efficiency technology and behavior influenced by development type and purpose.

The findings also indicate an opportunity for research to inform and calibrate energy code moving forward. Estimated model average variability suggests that design and construction for energy efficient units could be performed within tighter and more consistent values across the sample, which would result in increased overall unit efficiency. Regarding energy use, sample groups, such as new versus renovated units, and senior versus non-senior, contain internal variability while not ranging far from the overall sample average suggesting common factors to the affordable housing population. Variability is not increased by square footage, yet the number of people in the unit does seem to affect use. Research, therefore, suggests an opportunity for improved modeling tools.

This research has limitations. One limitation pertains to the difficulty in housing resident energy releases during data collection. The team, therefore, had an alternate plan for this possibility. When on-site collection processes did not work as planned, property managers were also asked to anonymously collect surveys left for residents. These releases collected by property managers constituted approximately 10% of all releases collected. Another limitation pertains to our sample that only reflect the energy efficiency of the multifamily houses within the affordable rental stock. The findings may not imply the energy use for commercial buildings.

Future work could extend this research as well. This work has found the existence of multiple impact factors, other than building technology, which critically influences a housing unit's energy usage. Research could benefit policy makers through further investigation of observed variables and how they impact residential energy efficiency. Another direction will be more investigation into a policy's impact on home builders, construction costs, and the correlation to savings from reduced utility bills.

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